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# Human Injury Criteria for Underwater Blasts

**R.M. Lance<sup>1</sup>**, B. Capehart, M.D.<sup>1,2</sup>, Omar Kadro, M.D.<sup>3</sup>, Cameron R. Bass, Ph.D.<sup>1</sup>

<sup>1</sup>*Duke University, Pratt School of Engineering, 136 Hudson Hall, Campus Box 90281, Durham, NC 27708*  
*rachel.lance@duke.edu*

<sup>2</sup>*Durham Veterans Administration Medical Center, 508 Fulton St, Durham, NC 27708*

<sup>3</sup>*William Beaumont Hospital, 1301 W. 13 Mile Rd, Royal Oak, MI 48073*

## 1. ABSTRACT

Underwater blasts propagate further and injure more readily than equivalent air blasts. Development of effective personal protection and countermeasures, however, requires knowledge of the currently unknown human tolerance to underwater blast. Current guidelines for prevention of underwater blast injury are not based on any organized injury risk assessment, human data or experimental data. The goal of this study was to derive injury risk assessments for underwater blast using well-characterized human underwater blast exposures in the open literature. The human injury dataset was compiled using 34 case reports on underwater blast exposure to 475 personnel, dating as early as 1916. Using severity ratings, computational reconstructions of the blasts, and survival information from a final set of 262 human exposures, injury risk models were developed for both injury severity and risk of fatality as functions of blast impulse and blast peak overpressure. Based on this human data, we found that the 50% risk of fatality from underwater blast occurred at  $600 \pm 170$  kPa-ms impulse. This risk value is the first impulse-based fatality risk calculated from human data. The gross inconsistency between the exposures in the case reports and the previously-available guidelines further underscored the need for this new guideline based on injury data.

## 2. INTRODUCTION

The lethal effects at a distance of underwater blasts have been known at least since the 1820s following the clearance and salvage of the Royal George in Portsmouth harbor in 1829 [1, 2]. Underwater blast injuries to humans were first described as the result of accidental depth charge detonations in 1916 during WWI [3]. Since then, the military and scientific communities have proclaimed the need for a realistic injury guideline for underwater blast exposures; however, even as recently as 2001 that need had yet to be fulfilled [4]. There is extensive literature on pulmonary injury and fatality risk assessments for air blast, some of the work driven by potential nuclear weapons exposure [5] and short and long peak overpressure duration military exposure (e.g. [6-8]). More recently, blast neurotrauma injury and fatality assessments have been derived [9, 10]. Much of this work was based on scaling animal risk assessments to human exposure conditions. Owing to differences in coupling between air/torso and water/torso, it is unclear how these air blast studies may apply to underwater blast injury risk.

Though underwater blasts propagate further and injure more readily than air blasts [11], the current U.S. Navy underwater risk guidelines are not based on actual blast exposure data. Instead, they are based entirely on the loose assertion that since the surface of the water “shreds” at approximately 3440 kPa (500 psi), the same pressure guideline must apply for tearing the inside of the human lungs [12]. This speculation has propagated through Navy literature since its original publication in 1943, and has never been updated through experimentation, theoretical calculations or any other means [13]. In fact, very few underwater blast injury guidelines have been based on data of any kind, and those guidelines that were based on data are still remarkably inconsistent in their recommendation of safe ranges from the blast [14]. This inconsistency is likely caused by the non-ideal setups and lack of appropriate inter-species scaling found in the majority of these experiments [15-19]. Despite the lack of accurate guidelines, military missions frequently expose personnel to underwater blast with an unquantified risk of injury or death. The purpose of this study was to use actual exposure data to create a meaningful underwater blast injury guideline.

## 3. BACKGROUND

While air blast injuries typically can occur via one of four general categories [20], the increased density and viscosity of water relative to air mean that underwater blast injuries occur almost exclusively as the

direct result of overpressure or primary blast. Similar to air blast, the gas-containing organs are by far the most affected in an underwater blast exposure. Occasional lesions of the liver occur [21, 22], but the majority of injuries occur through spalling of epithelium and microvasculature into air spaces in the lungs and intestinal tracts [23-26]. The prevalence and severity of intestinal damage is unique to underwater blast injuries. In addition, most available cases occur near the surface of the water. The importance of proximity to the surface on the resulting injury risk will be discussed in more detail in below.

Unlike for air blast, even ideal underwater blasts may not have a waveform that can be described using a Friedlander-like equation. Underwater blast waveforms are affected by numerous parameters including charge depth, bottom depth, gage depth, bottom reflectivity, and gas bubble fluctuations following detonation. Their effects on the shape of the blast waveform have been investigated exhaustively since the early 1940s and some are still the subject of active research [27-32]. Though the details of underwater blast physics are beyond the scope of this publication, there are two main points that are important to this study: 1) no research group has ever identified a Friedlander-like equation that accurately describes a generalized underwater blast waveform and 2) the surface of the water reflects a tension wave back down into the body of water that decreases the pressure of the primary waveform wherever the two intersect. This tension wave can result in a dramatic decrease both in peak pressure and in overall impulse for measurement points near the surface of the water. These decreases play an important role because the majority of human exposures to underwater blast have occurred at or near the surface of the water. Like air blasts, positive-pressure waves in underwater blasts are reflected off of surfaces with higher densities such as structures or the ocean bottom, but this effect is uncommon in human exposures unless the exposure occurs in shallow water or an enclosed space. Because of these complexities, descriptive parameters like peak pressure and impulse are often difficult to predict without advanced computational modeling.

The intensity of blast is well known to depend on more than one physical parameter that contributes to pressure or impulse time history. For ideal air blasts, the Friedlander waveform allows an indirect but comprehensive description of blast intensity through only two parameters, often peak pressure and positive phase duration. Many currently-available air blast injury criteria use these two parameters to describe exposure and therefore injury risk [cf. 5,6]. For the complex waveforms from underwater blasts, the entire shape of the curve is much more variable and a positive phase duration value is often difficult to determine. An actual impulse value is therefore a more comprehensive description of the overall blast waveform. The difficulty in precisely calculating or predicting impulse has lead most researchers to prescribe a guideline based on range or peak pressure, even though these factors have long been thought to be insufficient [14, 18, 28, 33, 34].

Though there are no simple theoretical models for underwater explosions, they can be accurately modeled using finite-element and finite-volume methods. These computational programs can account for the many factors that complicate underwater blasts [35, 36]. One of the most prominent pieces of modeling software is the US Navy's DYSMAS hydrocode, which uses the Gemini Eulerian solver to model the pressures resulting from underwater blasts. This software has been extensively validated and shown to accurately reproduce the effects of underwater blasts, even in complex environments [37, 38]. DYSMAS provided general pressure time histories based on ranges and explosives from the case literature to correlate with the observed injuries from underwater blast.

## **4. METHODS**

### **4.1 Injury ratings**

In contrast with air blast, there is a very limited amount of well-characterized experimental exposure data for underwater blast. However, during WWII at least as many military casualties were incurred from underwater blast as from air blast [39]. Hundreds of case reports of underwater blast exposure were published by military doctors, and many of these case reports contain extensive information about the scenario creating the blast exposure [3, 15, 24, 34, 40-57]. Much of this literature is based on experiences in WWII when sailors in the water were exposed to blasts from depth charges, either from enemy vessels or from primed charges that detonated as their own ships sank. In addition, a handful of more recent human experiments and isolated blast incidents have been published with details of the exposures [17, 21, 26, 58-62]. The resulting database had 475 human exposures at various ranges from the blasts, making it the largest underwater blast injury database compiled to date.

The injuries described ranged from mild abdominal discomfort and coughing to near-instantaneous fatalities. Many case studies contain comprehensive anatomical information, but frequently a detailed description of symptoms was the only medical information provided. Since modern injury rating systems do not rely upon symptoms alone, rating systems for both pulmonary and abdominal injuries were developed that included seven ordinal levels of severity. These numerical severity ratings were based on the reported symptoms, surgical findings, and autopsy reports. Severity estimates were derived from a collaboration of physicians and biomedical engineers including a colon and rectal surgeon with decades of experience treating intestinal abnormalities. For comparison, the injury ratings were associated with the AIS trauma injury scales for both pulmonary injuries [63] and abdominal injuries [64]. The ratings were designed to minimize the effect of differences in medical care across the cases, relying upon initial presentation of the patient rather than long-term prognosis. The rating scales are shown in Tables 1 and 2.

**Table 1.** Injury rating scale for abdominal injuries from underwater blast exposures. \*Modern medical standards mandate surgery for any size intestinal perforation. In contrast, surgery in the 1940s carried a large risk of infection, and antibiotics were far less available/effective. The decision to operate was used to assess, retrospectively, the severity of the patient's symptoms upon presentation, not to denote an acceptable modern medical standard of care.

<b>ABDOMINAL INJURY SCALE</b>			
<b>Rating</b>	<b>Severity</b>	<b>Symptomatic Scale</b>	<b>AIS Scales for Small Bowel/Colon/Rectum [64]</b>
0	None		
1	Minor	X-ray evidence; OR mild hemorrhaging; OR discomfort/pain; OR localized rigidity; NO general rigidity	Contusion or hematoma without devascularization; OR partial-thickness laceration without perforation
2	Moderate	Moderate hemorrhaging; OR discomfort/pain/general rigidity indicative of perforations deemed not to require surgery based on standards of treatment at time of injury*	Laceration <50% of circumference
3	Serious	Severe hemorrhaging; OR perforations severe enough to warrant surgery based on standards of treatment at time of injury*	Laceration ≥50% of circumference without transection
4	Severe	Multiple or unusually large perforations, possibly severe enough to cause death in 1943 but likely treatable by modern medical practices	Transection of small bowel/colon; Full-thickness laceration of rectum with extension into peritoneum
5	Critical	Untreatable in 1940s, would still likely be untreatable now; primarily palliative measures	Transection with segmental tissue loss in the small bowel/colon; OR devascularized segment in the small bowel/colon/rectum
6	Maximum	Fatality within 30 minutes of exposure	Maximal (currently untreatable)

**Table 2.** Injury rating scale for pulmonary injuries from underwater blast exposures.

<b>PULMONARY INJURY SCALE</b>			
<b>Rating</b>	<b>Severity</b>	<b>Symptomatic Scale</b>	<b>AIS Pulmonary Scale [63]</b>
0	None		
1	Minor	Some x-ray evidence but asymptomatic	Contusion (unilateral <1 lobe)
2	Moderate	Coughing; OR shallow breathing	Contusion (unilateral whole lobe); OR laceration (simple pneumothorax)
3	Serious	Mild hemoptysis; OR difficulty breathing	Contusion (unilateral >1 lobe); OR laceration (persistent >72hrs, airleak from distal airway); OR hematoma (nonexpanding intraparenchymal)
4	Severe	Severe symptoms, treatable by modern medical practice, possible recovery or fatality	Laceration (major airway leak); OR hematoma (expanding hematoma); OR vascular (primary branch intrapulmonary vessel disruption)
5	Critical	Severe cyanosis; OR severe hemoptysis; likely untreatable by modern medical practice; typically fatal	Vascular (hilar vessel disruption); OR multilobar lung laceration with tension pneumothorax
6	Maximum	Fatality within 30 minutes of exposure	Maximal (currently untreatable)

After the rating scales were developed, the injuries in the database were independently assigned a numerical severity by three different reviewers: a former-Army physician (MD) with prior blast trauma experience, an experienced PhD blast researcher, and a PhD student blast researcher. Each reviewer blindly and independently rated each injury according to the scales and the Cohen's kappa coefficient was calculated to determine inter-rate reliability between the MD and experienced PhD reviewers (0.42 for the abdominal scale, 0.54 for the pulmonary scale). The PhD student's ratings were only used as a tiebreaker to determine a final injury value for cases with conflicting reviewer values. The final Cohen's kappa coefficients between the MD reviewer's values and the final values were 0.65 and 0.70 for abdominal and pulmonary injuries respectively, and the coefficients for the experienced PhD reviewer were 0.71 and 0.77 respectively. These high kappa values indicate that the scale developed is sufficiently detailed to consistently describe the level of injury for the cases in the database.

#### **4.2 Blast assessment**

Many of the case reports contained sufficient detail to completely reconstruct the exposure scenarios, including charge type and estimated distance from the explosion center. Some of the publications issued during WWII did not contain detailed information on charge types because the information was still considered sensitive, but the charge types could be determined retroactively based on incident dates, vessels involved, locations, and personnel nationalities. Most of the exposures were depth charges, which had either a preset detonation depth or a very limited number of user-selectable detonation depths. Based on the depth charge model and the type of warfare being conducted when the vessel was sunk, the detonation depth could usually be determined fairly conclusively. If a case did not contain sufficient information to determine all of the scenario parameters, that case was eliminated from the final dataset.

Once the exposures were reconstructed, the US Navy's Gemini Eulerian solver was used to compute the peak pressures and impulses at the reported location of each blast injury victim. For blast victims with a head-out exposure while at the surface of the water, the lungs were approximated as 10 cm beneath the surface and the lower abdomen was approximated as 30 cm beneath the surface. Though these differences are generally a much shorter length scale than the horizontal separations from the charge, the resulting pressure time histories were sensitive to the distance of each organ system under the water. For example, this 20-cm distance typically yielded peak pressure and impulse values that differed by a factor of 2-3 owing to the tension wave reflecting off the surface of the water. The abdominal exposures were therefore significantly different from the pulmonary exposures for the same person ( $p < 0.001$  for both peak pressure and impulse values). Orientation in the water was reported in some case studies, but was generally not reported with enough frequency or descriptive detail to use it to determine vertical position on a finer scale.

#### **4.3 Protection**

Throughout the historical literature, authors repeatedly state their beliefs that life preservers should help mitigate the injurious effects of underwater blast in the lungs [12, 65]. These beliefs were stated without any evidence and were contended even as early as their initial publication in 1943 [53]. Recent investigation shows that modern personal protection in air blast offers substantial protection to the lungs [66], potentially increasing the relative occurrence of abdominal injuries [67]; however, the protection studied covers more of the chest and is much closer-fitting than the "Mae West" or belt-style life preservers of the time period.

While some testing has been performed to determine the protective effect of life preservers, the tests have either been inconclusive or determined that the area of protection needs to cover the entire torso to be effective [68, 69]. In the absence of experimental data, statistical analysis of the exposure dataset was performed to determine if wearing a life preserver provided a protective effect. Since the "life preserver" dataset was relatively small, the protective effect of life preservers was investigated by comparing relative injury levels between abdomen and pulmonary systems of protected and unprotected wearers. If life preservers provided protection to the lungs, then for a comparable level of pulmonary injury the abdominal injuries for personnel wearing life preservers should have been worse than for personnel who were not wearing life preservers.

Abdominal injury severity was plotted as a function of pulmonary injury severity for the 187 data points accounting for life preserver use. The personnel not wearing life preservers and the personnel

wearing life preservers were treated as two completely separate groups, and a linear model was fit to each set of data. The slopes of these lines were compared, and statistical significance was evaluated to determine the effect of life preservers. No significant effect could be detected, so life preserver use was eliminated as a statistical variable. The results of this analysis are presented below.

#### 4.4 Survival analysis

The injury levels for each organ system were separated into one of three groups: non-injury, injury, and fatality. Injury severity levels 0 and 1 were grouped as “non-injury” because level 1 injuries are, by definition, asymptomatic. Injury levels 2-4 were grouped as “injury” since the medical treatments for these levels would be similar and the patients would have a good chance of survival. Injury levels 5 and 6 were grouped as fatal because, even by modern standards, these patients would be considered beyond the capacity of medical treatment. While several level 4 cases resulted in fatalities, they were grouped as injuries because many of these cases died from infection and would likely be treatable with modern antibiotics, imaging, and surgical techniques.

Parametric survival analyses were performed for each organ system using Minitab (Version 17, Copyright ©2014, State College, PA, USA) resulting in four total impulse-based risk functions for blast exposure. The risk functions were in the form of a Weibull distribution:

$$f(I) = \frac{\beta}{\eta} \left(\frac{I}{\eta}\right)^{\beta-1} e^{-\left(\frac{I}{\eta}\right)^{\beta}} \quad (1)$$

When calculating the injury risk functions, severity levels 0-1 were considered as right-censored uninjured and levels 2-6 were considered interval-censored injuries, with possible injurious values between 0 and the calculated blast impulse. The same procedure was followed to determine the fatal risk functions, with injuries  $\leq 4$  considered nonfatal and injuries level 5-6 considered fatal. Cases that gave a range of possible distances were considered right-censored from the minimum possible exposure if an injury or fatality did not occur and interval-censored between 0 and the maximum possible exposure if an injury or fatality did occur.

#### 4.5 Range predictions

To provide safe distance estimates for underwater blast, the 1% and 50% risk values from the pulmonary and abdominal injury and fatality curves were translated into a function of range vs. charge weight using the experimentally-validated scaling law shown in Equation 2. The impulse values for injury were lower for the abdominal risk functions, while the impulse values for fatality were lower for the pulmonary risk functions. Injury or fatality risk by range is calculated by the system that gives the highest risk at the lowest impulse values.

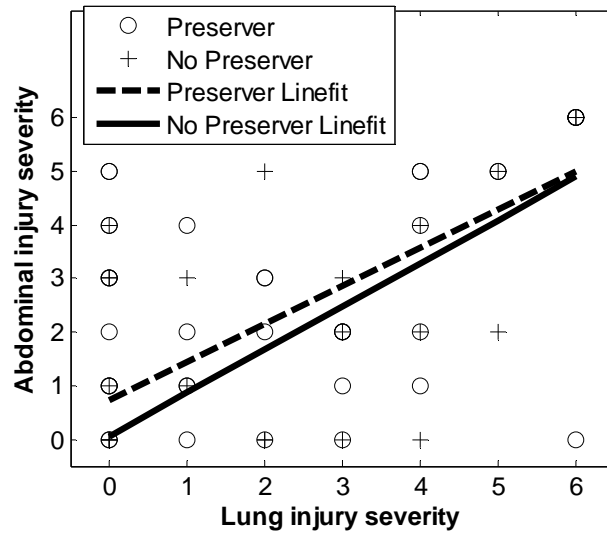
$$I = kW^{1/3} \left(\frac{W^{1/3}}{R}\right)^{\alpha} \quad (2)$$

Values for  $k$  and  $\alpha$  corresponding to TNT were used in this analysis. While TNT itself is rarely used for modern military purposes, it remains the standard for comparison of charge strengths. Owing to the tension wave reflected off the surface, Eq 2 describes only fully immersed cases that are away from the surface. Swimmers on the surface would be safe at greater distances than submerged swimmers because of the reduction in pressure from the reflected tension.

### 5. RESULTS

#### 4.1 Protection

The injury data and regression fit lines for the life preserver analysis are shown in Figure 1. Both regression lines are acceptable fits to the data (slope= 0.71, intercept= 0.76,  $R^2= 0.53$  with life preserver; slope= 0.81, intercept= 0.06,  $R^2= 0.75$  without life preserver).

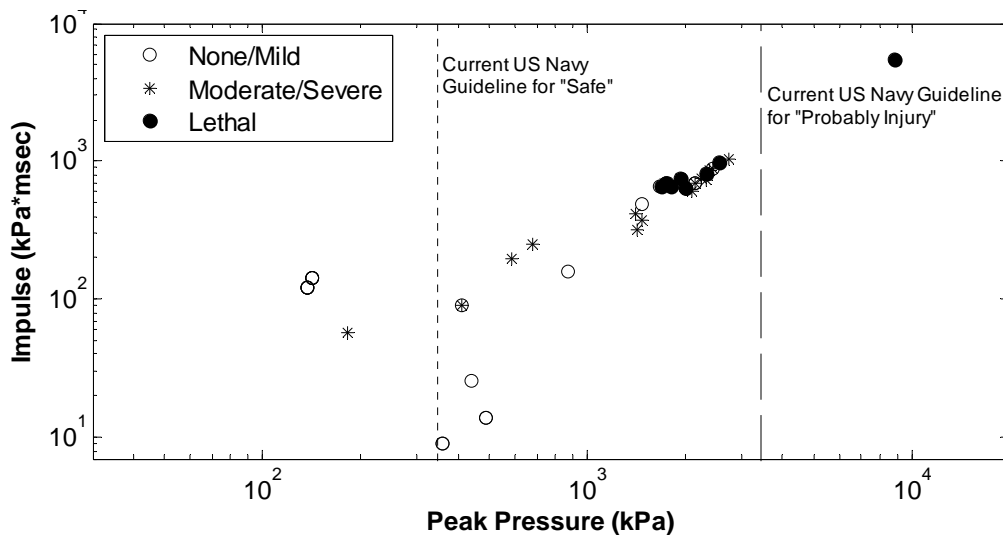


**Figure 1.** Abdominal injury severity as a function of pulmonary injury severity, for two groups wearing and not wearing life preservers at the time of blast exposure. Points on the graph may represent multiple data points.

While the  $R^2$  values are moderate, the p-values ( $<0.001$ ) for the slopes of both lines confirm that there is a statistically significant increase in abdominal injury severity with increasing pulmonary injury severity. This result is not surprising, since more severe injuries to both systems would logically result from an overall higher blast exposure. However, there is no significant difference between the slopes of the lines ( $p>0.42$ ). So, life preserver use was therefore eliminated as a variable in injury risk.

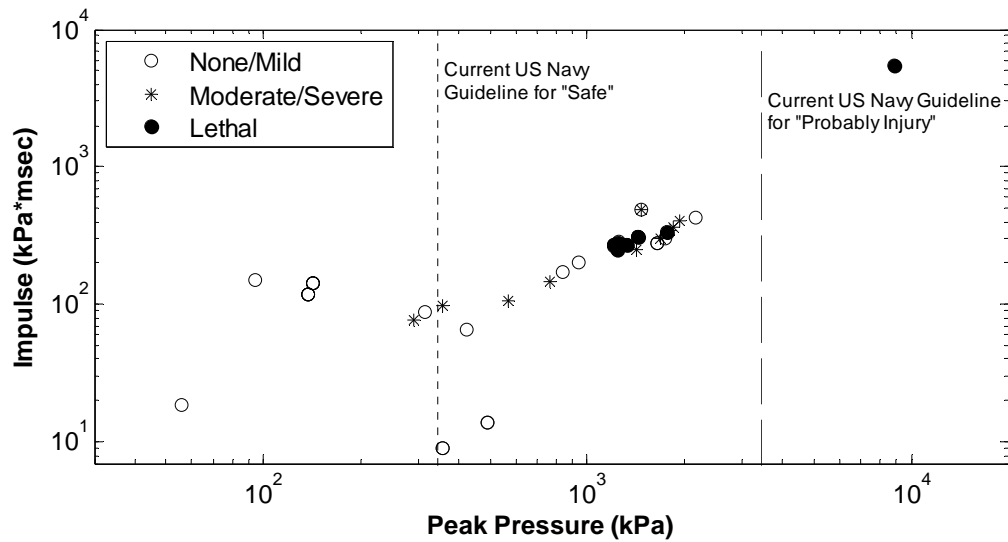
#### 4.2 Survival analysis

Figures 2a and 2b show the injury data for both organ systems plotted against peak pressure and impulse of exposure. For simplicity, cases with a range of possible distances are shown plotted at the exposure values corresponding to the mean distance. These results are compared with the current US Navy guidelines for safe exposure levels and probable injury threshold.



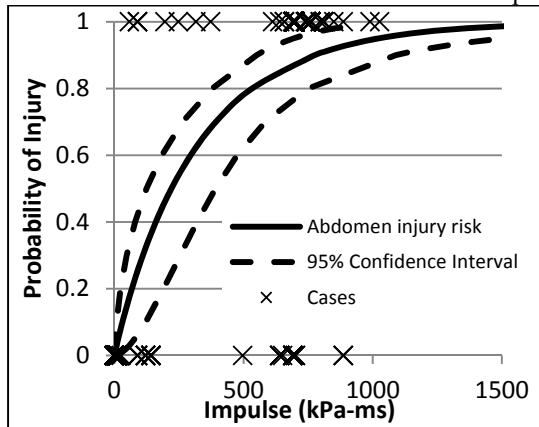
**Figure 2a.** Abdominal injuries.



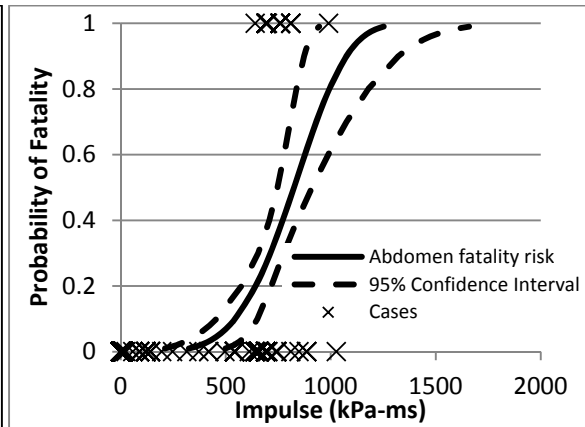


**Figure 2b.** Pulmonary injuries. Injuries plotted against peak pressure and impulse of exposure. Dotted and dashed lines represent current US Navy guidelines for “safe exposure” (50 psi, or 345 kPa) and “probable injury” threshold (500 psi, or 3447 kPa).

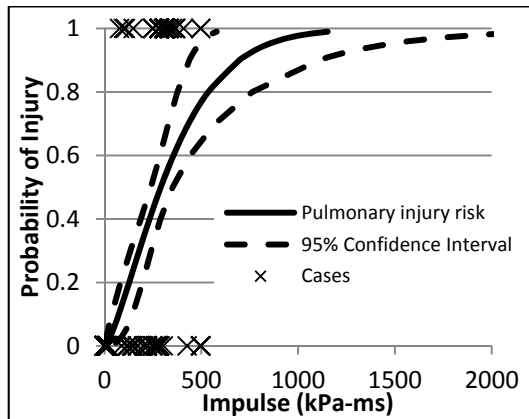
Figures 3 and 4 show the pulmonary and abdominal injury and fatality risk functions as computed by Minitab. The coefficients of the equations are shown in tabular form in Table 3.



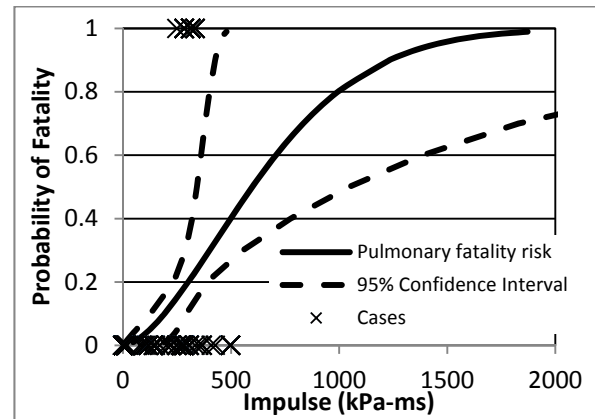
**Figure 3a.** Abdominal injury risk function.



**Figure 3b.** Abdominal fatality risk function.



**Figure 4a.** Pulmonary injury risk function.



**Figure 4b.** Pulmonary fatality risk function.

**Table 3.** Risk function equations and 50% risk values

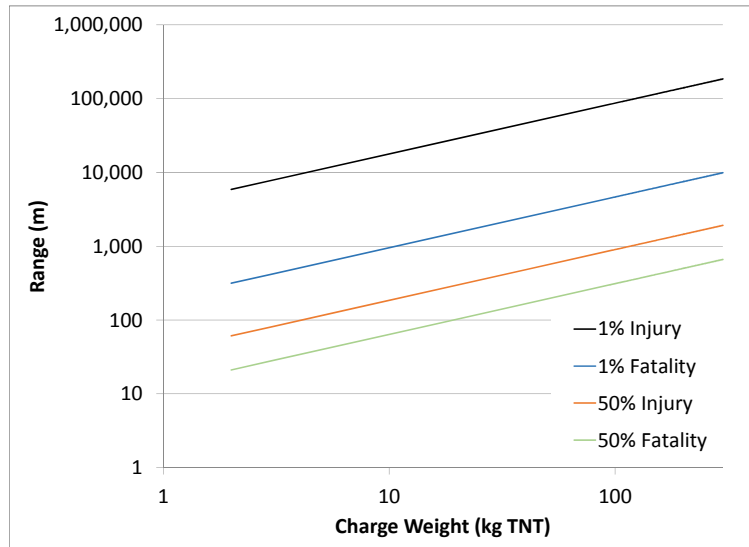
	<b>Injury Risk Function</b>		<b>Fatality Risk Function</b>	
<b>Abdominal</b>	$\beta = 0.954 ; \eta = 323.2$		$\beta = 4.538 ; \eta = 894.2$	
<b>Pulmonary</b>	$\beta = 1.373 ; \eta = 378.9$		$\beta = 1.659 ; \eta = 745.6$	

	<b>Injury Risk (kPa*ms)</b>		<b>Fatality Risk (kPa*ms)</b>	
	<b>1%</b>	<b>50%</b>	<b>1%</b>	<b>50%</b>
<b>Abdominal</b>	$3 \pm 3$	$220 \pm 65$	$325 \pm 71$	$825 \pm 42$
<b>Pulmonary</b>	$13 \pm 10$	$290 \pm 28$	$47 \pm 33$	$598 \pm 171$

### 4.3 Range predictions

The calculated range guidelines for immersion for injuries and fatalities are shown in Figure 3. The corresponding constants to compute range based on scaled impulse (manipulation of Eq 2) are described in Table 4. The two scaling constants for TNT,  $k$  and  $\alpha$ , were converted to Metric values from those found in Ref [70]. These curves predict ranges based on impulse for ideal explosives converted to a TNT standard. For a non-ideal explosive with a higher relative impulse value (e.g., aluminized charges), these range predictions will likely underestimate safe range.



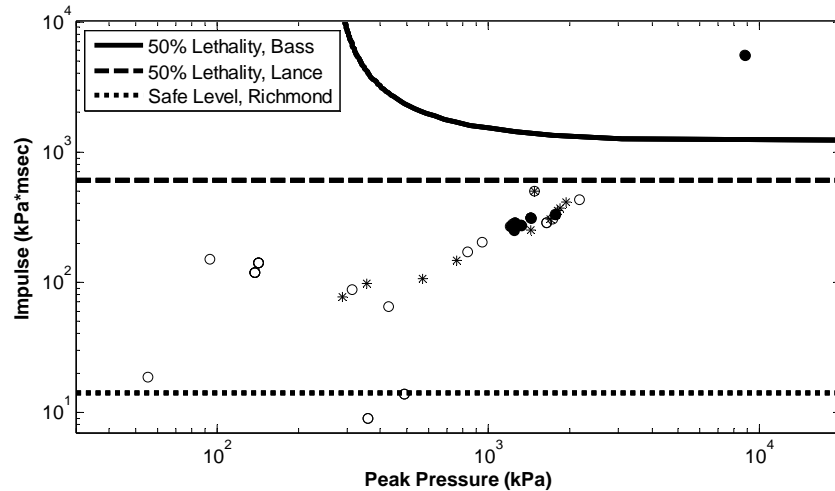
**Figure 3.** Predicted range for immersion injuries as a function of charge weight, 1% and 50% injury and fatality risk curves.

## 6. DISCUSSION

The current US Navy 500 psi guideline for ‘probable injury’ (dashed lines, Figures 2a and 2b) is qualitatively different than the results of the injury assessments from this study. *The largest grouping of human fatalities from underwater blast exposure has exposure levels that are lower than the US Navy ‘probable injury’ guidelines.* The safety guidelines developed by Richmond et al. [17, 72] are the most meticulously-developed standards to date, but even these were not based on human injury data. Instead, they were developed to assert safe levels only, and were based on extrapolations from animal data that were then given a factor of safety. In addition, the gauges in Richmond’s experiments were located 30 cm below the surface (12 in) with vertical swimmers at the surface, so the guidelines do not account for the increased impulses that would be seen by the lungs and chest if the diver were fully immersed.

The results of this study are compared directly with air blast fatality risk curves of Bass et al [6] as a function of peak pressure and impulse using a Friedlander approximation (Figure 5). For a blast peak pressure of 300 kPa, the corresponding ideal blast in air would have an impulse of 393 kPa\*ms. At this impulse level, this study predicts a 29% chance of fatality for pulmonary injuries and a 3% chance of fatality from abdominal injuries. This is consistent with the biomechanics of transmission of blast to the

chest in air compared with in water. It is expected that water transmission will be better coupled to the chest leading to lower impulse values for injury risk. Comparing Richmond's experiments with the current study, Richmond predicts a safe level of 14 kPa\*ms impulse for swimmers, while this study finds a 1% injury risk level at 3 kPa\*ms for the chest and 13 kPa\*ms for the abdomen. Since minor chest and abdominal injuries are unlikely to be diagnosed relative to major injuries, the results of this study and Richmond are similar in magnitude and are consistent.



**Figure 5.** Guidelines plotted with the pulmonary data from Figure 2b.

Previous investigators have suggested that impulse is a better correlate with human injury than peak pressure, but Figures 2a and 2b show that peak pressure and impulse are very highly correlated. So, statistical testing concluded that either could be used to accurately predict injuries for this dataset in contrast with the assertions of previous investigators. The dataset used in this study, however, almost exclusively contains exposures from ideal high explosives at the surface of an open body of water. In an enclosed space, or with non-ideal explosives, peak pressure and impulse are not always simply correlated. Experience with damage to underwater structures and pathobiology of air blast at long durations indicate that impulse should be a sensitive predictor of injury severity cf. [71], but it is difficult to demonstrate this without additional data from a wider variety of exposure types.

## 7. CONCLUSION

This study provides the first underwater blast injury risk functions based on human data. The dramatic difference between current US Navy guidelines and the available human data emphasizes the need for more realistic underwater blast guidelines. The current US Navy guideline for probable risk of injury falls at a peak pressure value higher than most of the fatalities in the current literature. The guidelines adopted from Richmond's experiments provide an impulse value for safe exposure, but are not frequently used because they do not provide a conversion from impulse to range. The Richmond guidelines also do not provide information about risk of injury or fatality should personnel be within the recommended range. Using the guidelines published in this study, for the first time military operators can reasonably estimate the risks from underwater blast exposure.

Previous literature suggested that the intestinal tract was more vulnerable to injury than the lungs in underwater blast. However, this study demonstrated that the abdominal cavity is not more vulnerable, instead it is exposed to substantially higher levels of blast when the victim is at the surface. Since the majority of historical exposures have occurred at or near the surface, the frequency of severe abdominal injuries has remained subject to this misinterpretation.

This model has several limitations, primarily based on its use of reconstructions based on historical data. While the DYSMAS hydrocode has been extensively validated, computational reconstruction will always introduce uncertainty compared with real-time measurement of values. In addition, the ranges provided were largely self-reported. Distressed sailors abandoning a sinking ship while swimming rapidly may provide only a gross estimation. At the beginning of the model development, this shortcoming was a

concern and was extensively tested. For any reported range, impulse and pressure values were also calculated for distances  $\pm 50\%$  of that range. Though this data is not presented here, typically variations of  $\pm 50\%$  range yielded peak pressure and impulse variations of about 3-4%, except for large ranges ( $>150$  m). This change was not large enough that the error in estimation prevented development of an accurate risk model.

This study is limited to ideal pressure profiles in open water. Future work may include long-duration, high-impulse explosive types and closed-environment data if available. This data would serve to better separate the influences of impulse and peak pressure for a wider range of applicability.

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